

Lessons from the Challenger Launch Decision¹



Figure 1: Challenger Crew (Left to Right): Ellison Onizuka, Michael Smith, Christa McAuliffe, Dick Scobee, Gregory Jarvis, Ronald McNair, and Judith Resnik. Source: NASA Image.

The Flight of the Space Shuttle *Challenger* on Mission 51-L began at 11:38 a.m. Eastern Standard Time (EST) on January 28, 1986 off the coast of Cape Canaveral, Florida. It ended 73 seconds later in an explosive burn of hydrogen and oxygen propellants that destroyed the external tank and exposed the *Orbiter* to severe aerodynamic loads that caused complete structural breakup. All seven crew members perished. The two Solid Rocket Boosters (SRB)² flew out of the fireball and were destroyed by the Air Force Range Safety Officer 110 seconds after launch. See **Figure 1** for an image of the Space Shuttle *Challenger* crew.

¹ This case is based primarily on excerpts taken directly from the Rogers' Commission testimony and final Report and has been edited for ease of reading, brevity, and clarity. For the complete record and testimony, see the full report on line at: <http://history.nasa.gov/rogersrep/genindex.htm>. See **Appendix 1** for a list of case references.

² There is a complete list of case acronyms in **Appendix 2**.

Launch Events

The ambient air temperature at launch was 36 degrees Fahrenheit. This temperature was 15 degrees colder than that of any previous launch. See **Figure 2**.

At 6.6 seconds before launch, the *Challenger's* liquid-fueled main engines were ignited in sequence and run up to full thrust, while the entire Shuttle structure was bolted to the launch pad. Thrust of the main engines bends the Shuttle assembly forward from the bolts anchoring it to the pad. When the Shuttle assembly springs back to the vertical, the SRBs' restraining bolts are explosively released. During this prerelease "twang" motion, structural loads are stored in the assembled structure. Those loads are released during the first few seconds of flight in a structural vibration mode at a frequency of about 3 cycles per second. The maximum structural loads on the aft field joints of the SRBs occur during the "twang", exceeding even those of the maximum dynamic pressure period experienced later in flight.

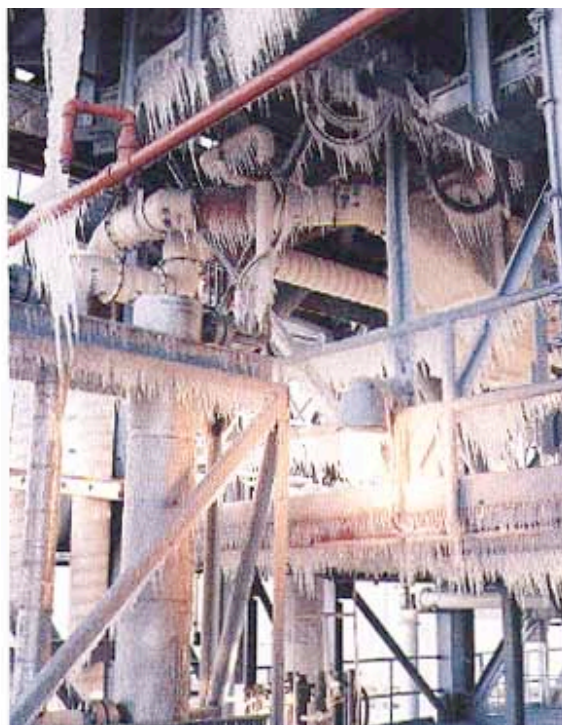


Figure 2: Ice on the Launch Tower Hours before the Launch. Source: NASA Image.



Figure 3: Grey Smoke Emitting from the Right-Hand SRB on Space Shuttle Challenger. Source: NASA Image.

Just after liftoff at 0.678 seconds into the flight, photographic data (**Figure 3**) shows a strong puff of gray smoke was spurting from the vicinity of the aft field joint on the right SRB. The computer graphic analysis of the film from the cameras indicated the initial smoke came from the 270- to 310-degree sector of the circumference of the aft field joint of the right SRB. This area of the solid booster faces the external tank. The vaporized material streaming from the joint indicated that there was not complete sealing action within the joint.

Eight more distinctive puffs of increasingly blacker smoke were recorded between 0.836 and 2.500 seconds. The smoke appeared to puff upwards from the joint. As the Shuttle increased its upward velocity, it flew past the emerging and expanding smoke puffs. The last smoke was seen above the field joint at 2.733 seconds.

Main engines had been throttled up to 104% thrust and the SRBs were increasing their thrust when the first flickering flame appeared on the right SRB in the area of the aft field joint. This

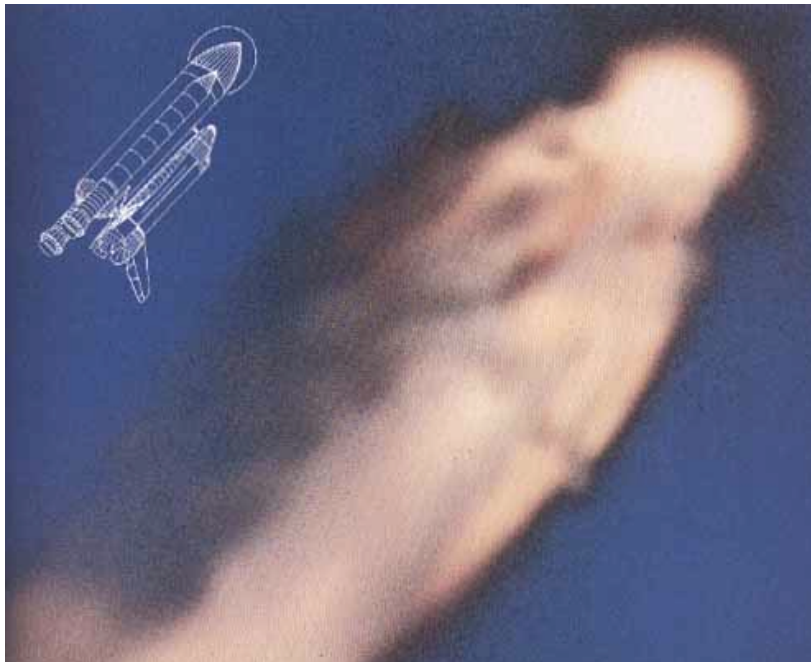
first very small flame was detected on image enhanced film at 58.788 seconds into the flight. It appeared to originate at about 305 degrees around the booster circumference at or near the aft field joint.

At about the same time (60 seconds), telemetry showed a pressure differential between the chamber pressures in the right and left boosters. The right booster chamber pressure was lower, confirming the growing leak in the area of the field joint.

As the flame plume increased in size, it was deflected rearward by the aerodynamic slipstream and circumferentially by the protruding structure of the upper ring attaching the booster to the external tank. Those directed the plume onto the surface of the external tank. The growing flame also impinged on the strut attaching the SRB to the external tank.

The first visual indication that swirling flame from the right SRB breached the external tank was at 64.660 seconds, when there was an abrupt change in the shape and color of the plume. This indicated that it was mixing with leaking hydrogen from the external tank. Telemetered changes in the hydrogen tank pressurization confirmed the leak. At about 72.20 seconds the lower strut linking the SRB and the external tank was severed or pulled away from the weakened hydrogen tank permitting the right SRB to rotate around the upper attachment strut.

At 73.124 seconds, a circumferential white vapor pattern was observed blooming from the side of the external tank bottom dome (see **Figure 4**). This was the beginning of the structural failure of the hydrogen tank that culminated in the entire aft dome dropping away. This released massive amounts of liquid hydrogen from the tank and created a sudden forward thrust of about



2.~3 million pounds, pushing the hydrogen tank upward into the intertank structure. At about the same time, the rotating right SRB impacted the intertank structure and the lower part of the liquid oxygen tank.

Figure 4: Rupture of the Liquid Oxygen Tank, which Occurred above the Booster/Tank Forward Attachment and Grew in Milliseconds to the Maximum Size Indicated in the Computer Drawing. Source: NASA Image.



Figure 5: Large Sections of the Orbiter Emerged from the Fireball. Source: NASA Image.

Within milliseconds, there was massive, almost explosive burning of the hydrogen streaming from the failed tank bottom and the liquid oxygen breach in the area of the intertank. The *Orbiter*, under severe aerodynamic loads, broke into several large sections, which emerged from the fireball (**Figure 5**). Separate sections that can be identified on film include the main engine/tail section with the engines still burning, one wing of the *Orbiter*, and the forward fuselage trailing a mass of umbilical lines pulled loose from the payload bay. The crew cabin with all the crew inside was found in 100 feet of water on March 8th. They were all still strapped in their seats. Some had activated supplemental oxygen. All would have died, when the cabin hit the water at an estimated 200 miles per hour if they survived the fall.

How O-Rings Work in the SRB

Enhanced photographic and computer-graphic positioning determined that the flame from the right SRB near the aft field joint emanated at about the 305-degree circumferential position. The smoke at lift off appeared in the same general location. Thus, early in the investigation the right SRB aft field joint seal became the prime failure suspect. This supposition was confirmed when the salvage team recovered portions of both sides of the aft joint where a hole had burned through that was 28 by 15 inches. Several possible causes could have resulted in this failure.

During stacking operations at the launch site, four segments were assembled to form the solid rocket motor. The resulting joints were referred to as field joints. Joint sealing was provided by two rubber O-rings with diameters of 0.280 inches (+0.005, -0.003), which were installed, as received from Morton Thiokol, during motor assembly. O-ring static compression during and after assembly was dictated by the width of the gap between the tang and the inside leg of the clevis. This gap between the tang and clevis at any location after assembly was influenced by the size and shape (concentricity) of the segments as well as the loads on the segments. Zinc chromate putty was applied to the composition rubber (NBR) insulation face prior to assembly. In the assembled configuration, the putty was intended to act as a thermal barrier to prevent direct contact of combustion gas with the O-rings. It was also intended that the O-rings be actuated and sealed by combustion gas pressure displacing the putty in the space between the motor segments.

The displacement of the putty would act like a piston and compress the air ahead of the primary O-ring, and force it into the gap between the tang and clevis. This process was known as pressure actuation of the O-ring seal. This pressure-actuated sealing was required to occur

very early during the solid rocket motor ignition transient, because the gap between the tang and clevis increased as pressure loads were applied to the joint during ignition. Should pressure actuation be delayed to the extent that the gap has opened considerably, the possibility existed that the rocket's combustion gases would blow by the O-ring and damage or destroy the seals. The principal factor influencing the size of the gap opening was motor pressure; but, gap opening was also influenced by external loads and other joint dynamics. See **Figure 6** and **Figure 7** for images of the SRB.

Figure 6: Cutaway View of the Solid Rocket Booster Showing Solid Rocket Motor Propellant and Aft Field Joint. Source: NASA Image.

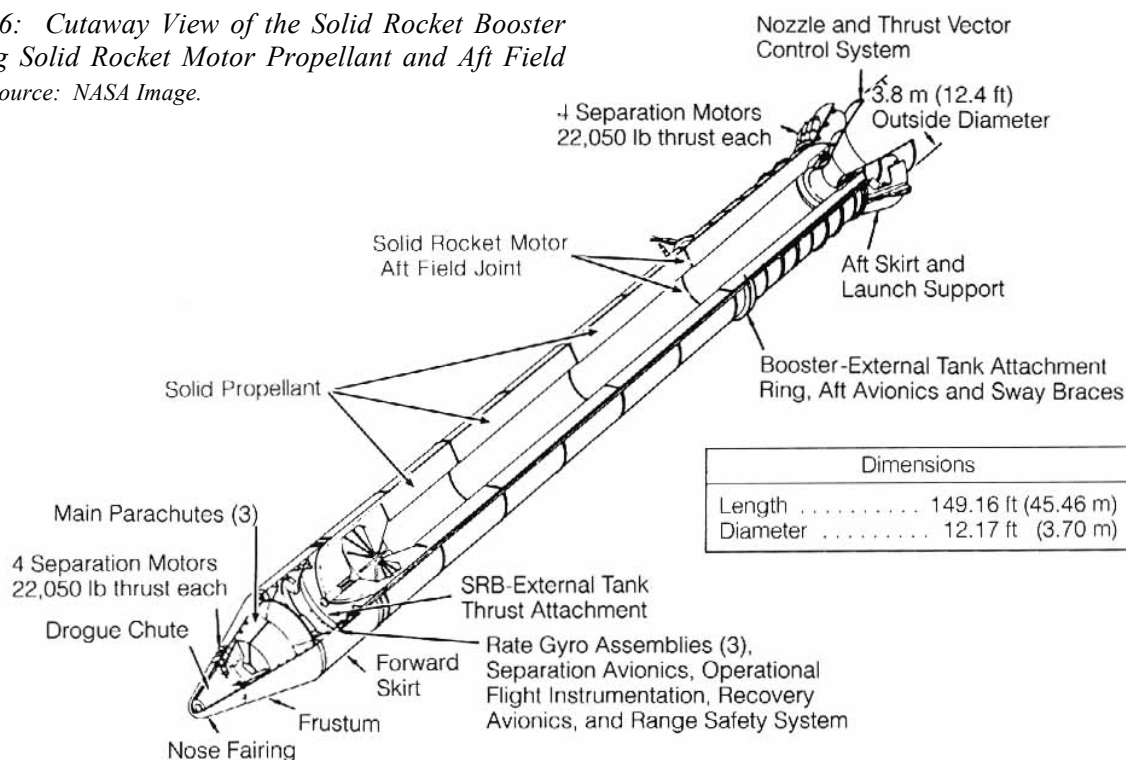
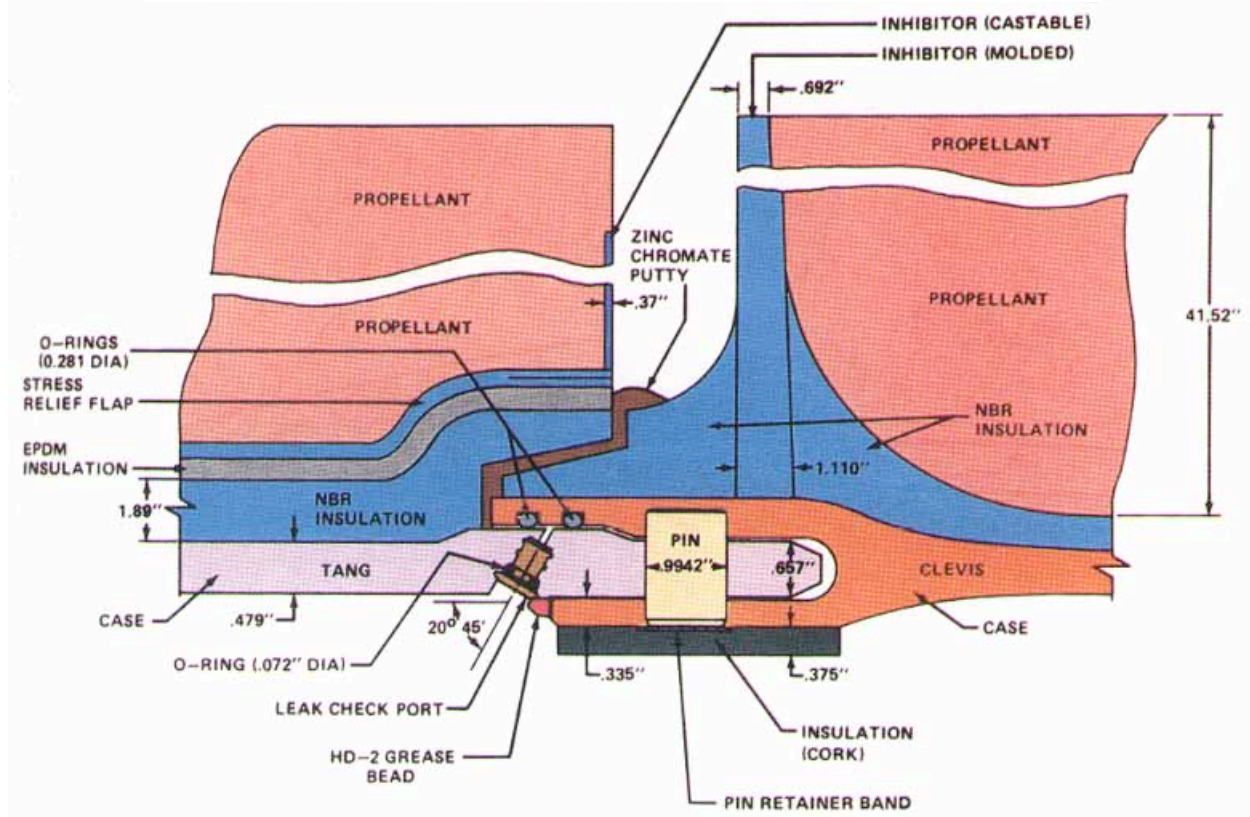
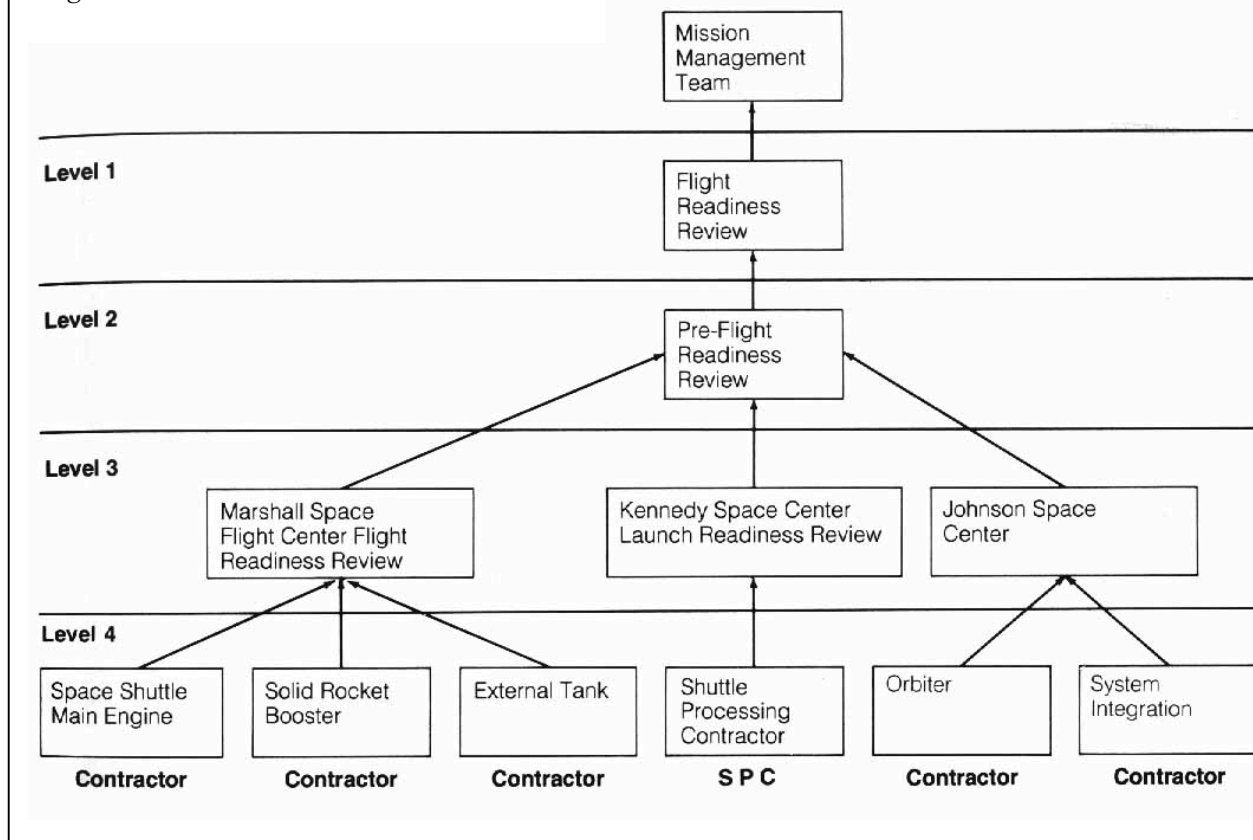


Figure 7: Aft Segment/Aft Center Segment Field Joint Configuration.
Source: NASA Image.



The Flight Readiness Review Process

The Shuttle Flight Readiness Review was a carefully planned, step-by-step activity, established by NASA program directive SPO-PD 710.5A, designed to certify the readiness of all components of the Space Shuttle assembly. The process was focused upon the Level-I Flight Readiness Review, held approximately two weeks before a launch. The Level-I Review (see **Figure 8**) was a conference chaired by the NASA Associate Administrator for Space Flight and supported by the NASA Chief Engineer, the Program Manager, the Center Directors, and Project Managers from the Johnson Space Center (JSC), the Marshall Space Flight Center (MSFC), and the Kennedy Space Center (KSC) along with senior Contractor representatives.

Readiness Reviews*Figure 8: Readiness Review. Source: NASA.***Evolution of NASA's Technical Culture**

NASA's original technical culture was characterized by a strong "in-house" technical competence across all of NASA's original organizations and personnel.

With the *Apollo* Program, increased complexity required hands-on Engineers to be converted into Executive Managers. Management systems initially developed in the Air Force were introduced to NASA. Key elements of this new management system included the following: concurrency, change control and configuration management, environmental testing, systems engineering, phased planning, and Project management.

Failures in the 1960s only resulted in further strengthening those methods, implementing more Project Reviews, and strengthening configuration control. In the decades that followed, with a reduced workforce (both civil servants and Contractors) and subtle shifts in engineering and management practices, the Agency's abilities weakened. Changes in leadership also had an impact. At MSFC, von Braun's habit of rewarding those who brought problems into the open was replaced by a "shoot the messenger" attitude with William Lucas. (Source: *NASA's First 50 years*, pp. 289–298.)

The formal portion of the process was initiated by directive from the Associate Administrator for Space Flight. The directive outlined the schedule for the Level-I Flight Readiness Review and for the steps that preceded it. The process began at Level IV with the Contractors formally certifying in writing the flight readiness of the elements for which they were responsible. Certification was made to the appropriate Level-III NASA Project Managers at JSC and MSFC. Additionally, at MSFC the Review was followed by a presentation directly to the Center Director. At KSC, the Level-III Review, chaired by the Center Director, verified the readiness of the launch support elements.

The next step in the process was the Certification of Flight Readiness to the Level-II Program Manager at JSC. In this review, each Space Shuttle Program element endorsed that it had satisfactorily completed the manufacture, assembly, test, and checkout of the pertinent element, including the Contractors' certification that design and performance were up to standard. The Flight Readiness Review process culminated in the Level-I Review.

In the initial notice of the Review, the Level-I directive established a Mission Management Team for the particular Mission. The team assumed responsibility for each Shuttle's readiness for a period commencing 48 hours before launch and continuing through post-landing crew egress and the safing of the *Orbiter*. On call throughout the entire period, the Mission Management Team supported the Associate Administrator for Space Flight and the Program Manager.

A structured Mission Management Team meeting-called L-1 was held 24 hours, or one day, prior to each scheduled launch. Its agenda included closeout of any open work, a closeout of any Flight Readiness Review action items, a discussion of new or continuing anomalies, and an updated briefing on anticipated weather conditions at the launch site and at the abort landing sites in different parts of the world. It was standard practice of Level-I and -II officials to encourage the reporting of new problems or concerns that might have developed in the interval between the Flight Readiness Review and the L-1 meeting, and between the L-1 and launch.

The Flight Readiness Review was held, as scheduled, on January 15. On the following day, Aldrich issued the schedule for the combined Level-I/Mission Management Team Meetings; he also announced plans for the Mission Management Team Meetings continuing throughout the Mission and included the schedule for the L-1 Review.

On January 23, Moore issued a directive stating that the Flight Readiness Review had been conducted on the 15th and that 51-L was ready to fly pending closeout of open work, satisfactory countdown, and completion of remaining Flight Readiness Review action items, which were to be closed out during the L-1 meeting. No problems with the SRB were identified.

Since December 1982, the O-rings had been designated a "Criticality 1" feature of the SRB design, a term denoting a failure point—without back-up—that could cause a loss of "life or vehicle if" the component failed. In July 1985, after a nozzle joint on STS 51-B showed erosion of a secondary O-ring, indicating that the primary seal failed, a launch constraint was placed on flight 51-F and subsequent launches. Those constraints had been imposed and regularly waived by the SRB Project Manager at MSFC, Lawrence B. Mulloy.

Neither the launch constraint, the reason for it, nor the six consecutive waivers prior to 51-L were known to Moore (Level I) or Aldrich (Level II) or Thomas at the time of the Flight

Readiness Review process for 51-L. There were other and independent paths of system reporting that were designed to bring forward information about the SRB joint anomalies. One path was the task force of Thiokol Engineers and MSFC Engineers, who had been conducting subscale pressure tests at Wasatch during 1985. Test data generated rising concern and frustration on the part of some of the Thiokol participants and a few of the MSFC participants. These were documented, but not reported to Level II. Another path was the examination at each Flight Readiness Review of evidence of earlier flight anomalies. For 51-L, the data presented in this latter path, while it reached Levels I and II, never referred to either test anomalies or flight anomalies with O-rings.

In the 51-L Readiness Reviews, it appeared that neither Thiokol management nor the MSFC Level-III Project Managers believed that the O-ring blow-by and erosion risk were critical.

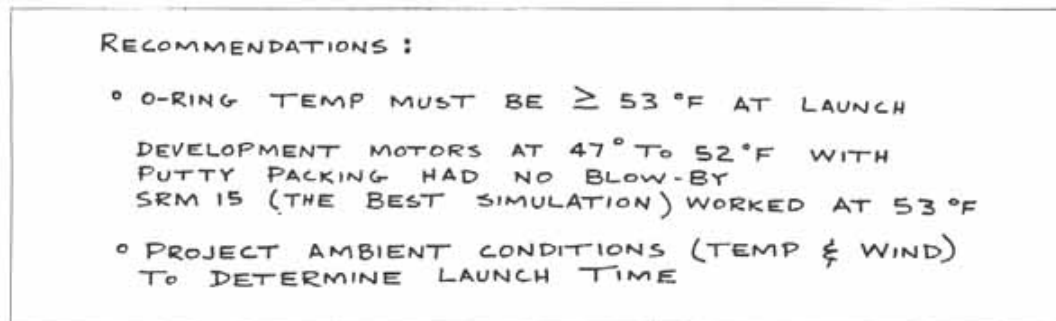
After a scrub due to high winds on the 27th of January, at 2:00 p.m. EST later that day, the Mission Management Team met again. At that time, the weather was expected to clear, but it appeared that temperatures would be in the low twenties for about 11 hours. Issues were raised with regard to the cold weather effects on the launch facility, including the water drains, the eye wash and shower water, fire suppression system, and overpressure water trays. It was decided to activate heaters in the *Orbiter*, but no concerns were expressed about the O-rings in the SRBs. The decision was to proceed with the countdown and with fueling, but all members of the team were asked to review the situation and call if any problems arose.

At approximately 2:30 p.m. EST, at Thiokol's Wasatch plant, Robert Ebeling, after learning of the predicted low temperature for launch, convened a meeting with Roger Boisjoly and with other Thiokol Engineers. Ebeling was concerned about predicted cold temperatures at KSC.

Later in the afternoon on the same day, Allan McDonald-Thiokol's liaison for the SRB Project at KSC received a telephone call from Ebeling, expressing concern about the performance of the SRB field joints at low temperatures.

Launch Operations Center said that they felt it ...would get as low as 22 degrees as a minimum in the early morning hours, probably around 6:00 o'clock, and that they were predicting a temperature of about 26 degrees at the intended time [of launch] about 9:38 the next morning.

In response, a teleconference was set up at KSC with the MSFC (NASA) managers, the Morton-Thiokol Managers and the Launch Operations Team. The first phase of the teleconference began at 5:45 p.m. EST; participants included Reinartz, Lovingood, Hardy, and numerous people at KSC, MSFC, and Thiokol-Wasatch. Concerns for the effect of low temperature on the O-rings and the joint seal were presented by Morton Thiokol, along with an opinion that launch should be delayed.



At approximately 8:45 p.m. EST, Phase 2 of the teleconference commenced, because the Thiokol charts and written data had arrived at KSC by fax. The charts presented a history of the O-ring erosion and blow-by in the SRB joints of previous flights, presented the results of subscale testing at Thiokol and the results of static tests of solid rocket motors.

Testimony about the Teleconferences³

Mr. Roger Boisjoly: I expressed deep concern about launching at low temperature. I presented **Chart 2-1**.... It addresses the highest concern of the field joint in both the ignition transient condition and the steady state condition, and it really sets down the rationale for why we were continuing to fly. Basically, if erosion penetrates the primary O-ring seal, there is a higher probability of no secondary seal capability in the steady state condition.

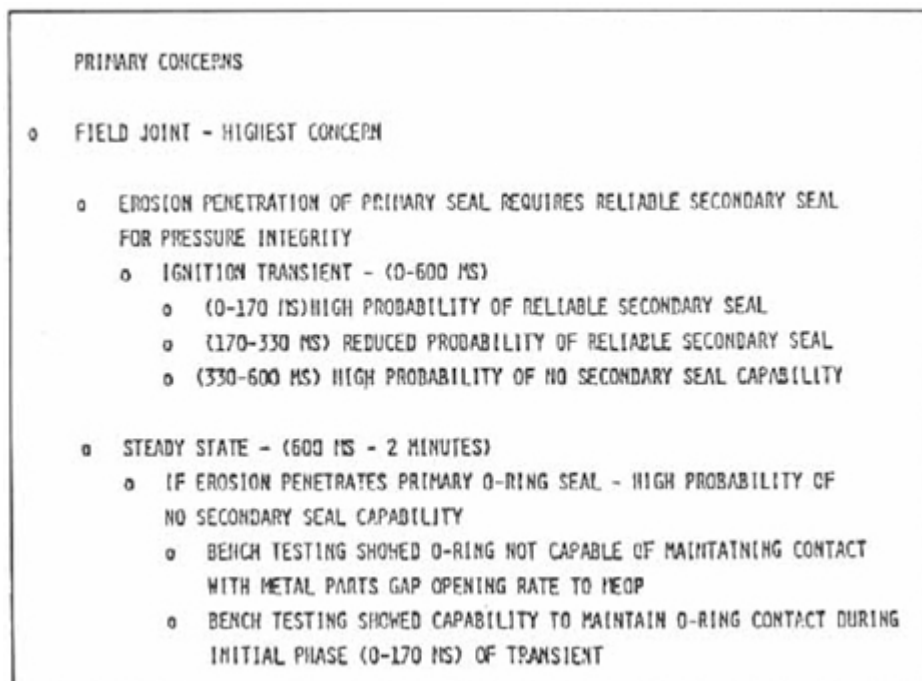


Chart 2-1: Presented by Thiokol's Roger Boisjoly Summarizing Primary Concerns with the Field Joint and Its O-Ring Seals on the Boosters. Source: NASA.

³ The testimony presented here is extracted from the Report of the Presidential Commission on the Space Shuttle *Challenger* Accident (aka Rogers Commission Report), Vol. 4, Testimony of February 26, 1986. Available at: <http://history.nasa.gov/rogersrep/v4part7.htm#4>. Accessed on July 21, 2014.

Joint Primary Concerns	SRM 25
■ A Temperature Lower Than Current Data Base Results in Changing Primary O-Ring Sealing Timing Function	
■ SRM 15A—80° ARC Black Grease Between O-Rings	
■ SRM 15B—110° ARC Black Grease Between O-Rings	
■ Lower O-Ring squeeze due to lower temp.	
■ Higher O-Ring shore hardness	
■ Thicker grease viscosity	
■ Higher O-Ring pressure actuation time	
■ If actuation time increases, threshold of secondary seal pressurization capability is approached	
■ If threshold is reached then secondary seal may not be capable of being pressurized	

Boisjoly's Chart 2-2 indicating concern about temperature effect on seal actuation time (handwritten).

I then presented Chart 2-2 with added concerns related to the timing function. And basically on that chart, I started off talking about a lower temperature than current data base results in changing the primary O-ring sealing timing function,...

We would have higher O-ring pressure actuation time, in my opinion, and that is what I presented.... These are the sum and substance of what I just presented. If action time increases, then the threshold of secondary seal pressurization capability is approached. That was my fear. If the threshold is reached, then the secondary seal may not be capable of being

pressurized, and that was the bottom line of everything that had been presented up to that point.

Someone on the Internet commented that we had soot blow-by on the solid rocket motors (SRM)-22 [Flight 61-A, October 1985], which was launched at 75 degrees. I don't remember who made the comment, but that is where the first comment came in about the disparity between my conclusion and the observed data because SRM-22 [Flight 61-A, October 1985] had blow by at essentially a room-temperature launch.

I then said that SRM-15 [Flight 51-C, January 1985] had much more blow-by indication and that it was indeed telling us that lower temperature was a factor. This was supported by inspection of flown hardware by myself. I was asked again for data to support my claim, and I said I have none other than what is being presented, and I had been trying to get resilience data, Arnie and I both, since last October, and that statement was mentioned on the Internet.

Chairman William Rogers: What was the conclusion?

Mr. Boisjoly: The conclusion was we should not fly outside of our data base, which was 53 degrees. Those were the conclusions. And, we were quite pleased because we knew in advance, having participated in the preparation, what the conclusions were, and we felt very comfortable with that.

It was about that time that Mr. George Hardy from MSFC was asked what he thought about the MTI [Morton Thiokol, Inc.] recommendation, and he said he was appalled at the MTI decision. Mr. Hardy was also asked about launching, and he said no, not if the Contractor recommended not launching, he would not go against the Contractor and launch.

Mr. Joe Kilminster was asked by NASA if he would launch, and he said “no”, because the engineering recommendation was not to launch.

Then MTI management asked for a five-minute caucus. I’m not sure exactly who asked for that, but it was asked in such a manner that I remember it was asked for, a five-minute caucus, which we put on—the line on mute and went off-line with the rest of the Internet.

Mr. Boisjoly: Okay, the caucus started by Mr. Jerry Mason stating a management decision was necessary. Those of us who opposed the launch continued to speak out, and I am specifically speaking of Mr. Arnold Thompson and myself because in my recollection he and I were the only ones that vigorously continued to oppose the launch. And we were attempting to go back and rereview and try to make clear what we were trying to get across, and we couldn’t understand why it was going to be reversed. So we spoke out and tried to explain once again the effects of low temperature. Arnie [Arnold Thompson] actually got up from his position which was down the table, and walked up the table and put a quarter pad down in front of the table, in front of the management folks, and tried to sketch out once again what his concern was with the joint, and when he realized he wasn’t getting through, he just stopped.

I tried one more time with the photos. I grabbed the photos, and I went up and discussed the photos once again and tried to make the point that it was my opinion from actual observations that temperature was indeed a discriminator and we should not ignore the physical evidence that we had observed.

And again, I brought up the point that SRM- 15 [Flight 51 -C, January 1985] had a 110 degree arc of black grease, while SRM-22 [Flight 61-A, October 1985] had a relatively different amount, which was less and wasn’t quite as black. I also stopped when it was apparent that I couldn’t get anybody to listen.

Dr. Walker: At this point, did anyone else speak up in favor of the launch?

Mr. Boisjoly: After Arnie and I had our last say, Mr. Mason said we have to make a management decision. He turned to Bob Lund and asked him to take off his engineering hat and put on his management hat. From this point on, management formulated the points to base their decision on.

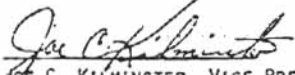
Chairman Rogers: How do you explain the fact that you seemed to change your mind when you changed your hat?

Mr. Lund: I guess we have got to go back a little further in the conversation than that. We have dealt with MSFC for a long time and have always been in the position of defending our position to make sure that we were ready to fly, and I guess I didn’t realize until after that meeting and after several days that we had absolutely changed our position from what we had been before. But that evening I guess I had never had those kinds of things come from the people at MSFC. We had to prove to them that we weren’t ready, and so we got ourselves in the thought process that we were trying to find some way to prove to them it wouldn’t work, and we were unable to do that. We couldn’t prove absolutely that that motor wouldn’t work.

Chairman Rogers: In other words, you honestly believed that you had a duty to prove that it would not work?

MTI ASSESSMENT OF TEMPERATURE CONCERN ON SRM-25 (51L) LAUNCH

- 0 CALCULATIONS SHOW THAT SRM-25 O-RINGS WILL BE 20° COLDER THAN SRM-15 O-RINGS
- 0 TEMPERATURE DATA NOT CONCLUSIVE ON PREDICTING PRIMARY O-RING BLOW-BY
- 0 ENGINEERING ASSESSMENT IS THAT:
 - 0 COLDER O-RINGS WILL HAVE INCREASED EFFECTIVE DUROMETER ("HARDER")
 - 0 "HARDER" O-RINGS WILL TAKE LONGER TO "SEAT"
 - 0 MORE GAS MAY PASS PRIMARY O-RING BEFORE THE PRIMARY SEAL SEATS (RELATIVE TO SRM-15)
 - 0 DEMONSTRATED SEALING THRESHOLD IS 3 TIMES GREATER THAN 0.038" EROSION EXPERIENCED ON SRM-15
- 0 IF THE PRIMARY SEAL DOES NOT SEAT, THE SECONDARY SEAL WILL SEAT
 - 0 PRESSURE WILL GET TO SECONDARY SEAL BEFORE THE METAL PARTS ROTATE
 - 0 O-RING PRESSURE LEAK CHECK PLACES SECONDARY SEAL IN OUTBOARD POSITION WHICH MINIMIZES SEALING TIME
- 0 MTI RECOMMENDS STS-51L LAUNCH PROCEED ON 28 JANUARY 1986
 - 0 SRM-25 WILL NOT BE SIGNIFICANTLY DIFFERENT FROM SRM-15


JOE C. KILMINSTER, VICE PRESIDENT
SPACE BOOSTER PROGRAMS

MORTON THIOKOL, INC.
Wasatch Division

Mr. Robert Lund: Well, that is kind of the mode we got ourselves into that evening. It seems like we have always been in the opposite mode. I should have detected that, but I did not, but the roles kind of switched. See **Appendix 3** for a list of individuals mentioned in the case study.

Appendix 1

Case References

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Appendix 2

Case Acronyms

EST	Eastern Standard Time
JSC	Johnson Space Center
KSC	Kennedy Space Center
MSFC	Marshall Space Flight Center
MTI	Morton Thiokol, Inc.
SPC	Shuttle Processing Contractor
SRB	solid rocket boosters
SRM	solid rocket motors

Appendix 3

Individuals Mentioned in this Case

- Arnold D. Aldrich, Space Shuttle Program Manager
- Jesse Moore, Associate Administrator for Space Flight
- James A. (Gene) Thomas, Deputy Director of Launch and Operations, KSC
- Stanley R. Reinartz, Manager, Shuttle Projects Office
- Judson A. Lovingood, Deputy Manager, Shuttle Projects Office
- George Hardy, Deputy Director of Science and Engineering, MSFC
- Lawrence B. Mulloy, Manager, SRB Project, MSFC
- Roger Boisjoly, Member, Seal Task Force, Morton Thiokol Wasatch Division
- Robert K. Lund, Vice President, Engineering, Morton Thiokol Wasatch Division
- Robert Ebeling, Manager, Ignition System and Final Assembly, SRB Project, MTI
- Allan McDonald, Director, SRM Project, MTI
- Joe C. Kilminster, Vice President, Space Booster Program, MTI
- Arnold Thompson, Supervisor, Rocket Motor Cases, MTI
- Jerry Mason, Senior Vice President for Wasatch Operations, MTI
- William P. Rogers, Chairman of the Presidential Commission on the Space Shuttle *Challenger* Accident.